

Temporal Variability of Stars and Stellar Systems

A White Paper for the Stars and Stellar Evolution Science Frontier Panel
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1 Introduction

Although the Sun is our closest star by many orders of magnitude and despite having sunspot records stretching back to ancient China, our knowledge of the Sun's magnetic field is far from complete. Indeed, even now, after decades of study, the most obvious manifestations of magnetic fields in the Sun (e.g. sunspots, flares and the corona) are scarcely understood at all. These failures in spite of intense effort suggest that to improve our grasp of magnetic fields in stars and of astrophysical dynamos in general, we must broaden our base of examples beyond the Sun; we must study stars with a variety of ages, masses, rotation rates, and other properties, so we can test models against as broad a range of circumstances as possible.

Although optical interferometry continues to make great strides (e.g. Monnier et al. 2007; Zhao et al. 2008), the tiny angular sizes of most stars will make direct imaging of stellar surface features very difficult. This means that we will have to rely on indirect methods to obtain information about the surfaces of cool stars and their environment. Over the next decade, this array of techniques will be supplemented by rapidly maturing new capabilities such as gyrochronology, asteroseismology and precision photometry from space, which will transform our understanding of the temporal variability of stars and stellar systems. In the next sections we will outline some of the key science questions in this area along with the techniques that could be used to bring new insights to these questions.

2 Understanding the Rotation of Stars

The surface rotation is an observable feature of stars that bears the imprint of such fundamental processes as accretion, mass loss, time evolution of internal flows and structure, and the action of magnetic fields. Relating observed phenomenology to underlying physics is difficult, however. For example, Solar-type stars with ages between that of the Hyades (~ 625 Myr) and of the Sun have observed rotation rates which are well-described by the Skumanich $\omega \sim t^{-1/2}$ law (Soderblom 1983). But young clusters (~ 50 – 100 Myr) show a spread in rotation rates at a given mass, with a population of ‘ultrafast rotators’ that are not seen in the older clusters (e.g. Stauffer et al. 1989). Why do young stars show such a large spread in rotation rate at each mass? Models to address this question often invoke saturation of the angular momentum loss above some critical angular velocity ω_{sat} . Yet there is evidence (e.g. Irwin et al. 2007) that even this is insufficient and that core-envelope rotational decoupling is needed to explain the slowest rotators in open clusters. So what are the important processes leading to the rotation distribution, and how do they work? Such questions have in the past been nearly unanswerable, for lack of relevant observations and adequate supporting theory. In the next decade, there is for the first time an opportunity to address both of these failings.

Improved technology now allows major improvements in the fidelity, sample size, and time coverage available to conventional kinds of observations. Thus, a concerted effort using existing or planned wide-field imagers and multi-object spectrographs would yield information of unprecedented quality and homogeneity about rotation and magnetic fields on large samples of cluster stars. Moreover, just as helioseismology has revolutionized the understanding of the internal structure and rotation of the Sun (e.g. Christensen-Dalsgaard 2004), asteroseismology is now poised to extend this knowledge to a much greater range of stars. Asteroseismology-capable space missions such as CoRoT and Kepler, as well as ground-based seismology networks such as SONG (the Stellar Oscillations Network Group – Grundahl et al. 2008) will yield meaningful estimates of stellar convection zone depths (Monteiro et al. 2000; Verner et al. 2006), and also of the depth dependence of the angular velocity in stars.

In addition to observational progress, great strides are expected in the theoretical and computational resources that can be applied to the problem of stellar rotation. Advances in 3-dimensional MHD models (e.g. Rempel et al. 2009) combined with insights about meridional and other large-scale flows (e.g. Jouve et al. 2008) may provide a theoretical basis for interpreting the anticipated new, highly detailed observational data. This combination may for the first time lead to a quantitative understanding of the rotation of stars.

3 Determining the Ages of Stars

A star’s age is one of its most fundamental parameters, yet it is the most difficult to measure, particularly for objects in the field. The internal structure and composition of stars are expected to evolve on different paths throughout the star’s life, depending on the initial conditions. But it is hard to constrain evolutionary models relating observed stellar characteristics (such as luminosity, radius, metallicity, rotation, chromospheric activity) with the underlying physical processes (convection, mixing, radiative transport, magnetic dynamo etc.) when the age of the subject cannot be established. This flaw has been sharply highlighted by recent exoplanet discoveries, in which the corresponding theoretical work on the formation and evolution of planet-hosting star systems (Melo et al., 2006; Saffe et al., 2005) has been hampered by ignorance of the host star’s age.

In recent years, a new technique in stellar age-dating has become available, in addition to improvements in the precision of traditional methods (e.g. measuring the lithium depletion, chromospheric activity, asteroseismology and isochrone fitting to HR diagrams Mamajek et al. 2007). Barnes (2007) established clear relationships describing stellar ages as a function of rotation rates and star color. Although currently the technique can be applied only to solar-type (FGKM) stars over ~ 200 Myr whose rotation rates can be measured, it can be used to date field stars.

Currently, multiple age-dating techniques are being applied to clusters and other targets for which the age can be corroborated (e.g. Meibom et al. 2008). Confusingly, although the systems should be coeval, different methods yield different ages. It is unclear whether this can be interpreted in terms of a spread in the times of star formation. In the near future, we

anticipate this work being extended to targets spanning wider ranges in age, metallicity etc. This will be complemented by advances in multidimensional hydrodynamical simulations of stellar structure, which aim to improve our understanding of the effects of physical processes such as rotation, convection, composition and radiation transport on the accuracy of theoretical evolutionary tracks (Mamajek et al., 2007).

Over the next decade a number of keynote projects will provide unparalleled survey data ideal for dating statistically significant samples of stars by multiple methods. The MOST (Microvariability and Oscillations of Stars) (Walker et al., 2003) and CoRoT (Baglin et al., 2006) missions are already paving the way, providing high precision, continuously-sampled lightcurves of thousands of stars. The modulation of the lightcurves due to starspots makes it easy to determine stellar rotation rates and hence apply gyrochronology, in addition to asteroseismology techniques, providing a dual constraint on age. Kepler (Borucki et al., 2007), to be launched this year, will monitor another extensive sample of $\sim 100,000$ main sequence stars (including 4 open clusters), many of which are expected to host planets. Furthermore, we look forward to the capabilities of the planned ground-based 1–2m-class telescope networks, such as SONG and LCOGT, to provide high cadence, continuous, time series photometry and spectroscopy. This will enable extensive asteroseismology and stellar rotation studies of diverse stellar populations, for which ages can now be derived.

4 Time Evolution of Stellar Activity

The Sun is variable in a wide variety of ways and on a large range of timescales. Somewhat surprisingly given the length of records of sunspots, the mean 11 year periodicity in sunspot number was identified only about a century and a half ago (Schwabe, 1843; Eddy, 1977). Other periodicities have also been detected and on top of this regular cyclic behavior are occasional absences of any activity for prolonged lengths of time. However there is still considerable controversy even for the Sun about how and where the field is generated and what physical processes (differential rotation, meridional flow) control the magnetic cycle. (e.g. Charbonneau 2005)

How can other stars help? Stars other than the Sun can be found at nearly any age, mass and rotation period and provide a direct way of studying how the dynamo processes depend on fundamental properties such as mass (and hence convective zone depth) and rotation rate. It has been shown even for the ‘solar twins’ with long-term measurements (Hall et al., 2007), that the dynamo can be very sensitive to the basic parameters or rotation and mass and may depend on additional parameters such as Li abundance. Clearly studying the dynamo processes over a wide range of the potential parameter space is vital.

M dwarf stars are particularly interesting as they become fully convective (and therefore lack an interface layer where dynamo processes concentrate in the Sun) but nevertheless possess strong magnetic fields and activity (e.g. Johns-Krull and Valenti 1996; Delfosse et al. 1998). Part of this activity manifests itself in the form of intense flares spanning the electromagnetic spectrum from the X-ray to the radio. Since M dwarfs comprise about 70% of stars in our Galaxy, these flares will be a significant, even dominant, source of transients

in the time-domain surveys planned for the next decade, such as PTF¹, Pan-STARRS² and LSST³. Clearly determining the nature of the magnetic dynamo in low-mass stars will be crucial for understanding the transient universe revealed by the synoptic surveys. But beyond minimizing their nuisance to other science, the sources and mechanisms of magnetic activity in M dwarfs is worth studying on its own terms, as a further probe of hydromagnetic processes in stars. Previously this issue has been hard to address, but new instruments and observations (Donati et al. 2008) and improved theory and numerical simulation (Browning 2008; Ludwig and Steffen 2008) will allow deeper understanding of these stars.

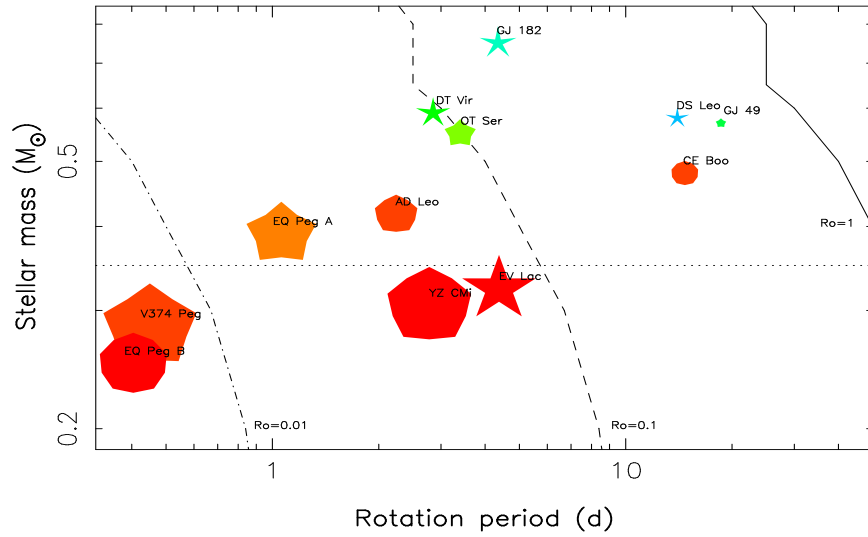


Figure 1: Properties of large-scale magnetic properties of early and mid-M dwarfs (from Donati et al. 2008). Symbol size indicates field strength, symbol color indicates field configuration (blue: purely toroidal, red: purely poloidal) and shape indicates degree of axisymmetry (decagon: purely axisymmetric, stars: purely non-axisymmetric). The theoretical fully-convective boundary is shown at $M_* \simeq 0.35M_\odot$.

Investments in new high resolution IR spectrographs and spectropolarimeters will allow study of a large sample of M dwarfs with unprecedented accuracy and sampling frequency. In addition, there will be a great increase in computing power over the next decade, allowing numerical simulations to increase in spatial/wavelength resolution and to model physical effects that are not currently included. The resulting confrontations between observation and theory may lead towards a coherent picture of dynamo processes in stars.

¹Palomar Transient Factory (<http://www.astro.caltech.edu/ptf/>)

²<http://pan-starrs.ifa.hawaii.edu/public/>

³<http://www.lsst.org>

5 Connections to asteroseismology and to exoplanets

There are many other areas of astronomy and physics in general that overlap and are influenced by the study of stellar magnetic fields. The study of the Sun and its activity with facilities such as the ATST⁴ and SDO⁵, along with techniques like helioseismology, will allow magnetic fields in our closest star to be studied in great detail.

The pace of progress in dynamo modeling accelerated after helioseismology provided meaningful constraints on the Sun's interior structure and dynamics (Brown et al., 1989). Later observations, able to detect helioseismic signatures of solar cycle effects, established that variations in the mean strength of the solar magnetic field cause shifts of up to ($\sim 0.5 \mu\text{Hz}$) in the frequencies of even the lowest-degree p-modes (Libbrecht and Woodard 1990; Salabert et al. 2004). Space-based photometric asteroseismology missions, such as MOST (Walker et al., 2003), CoRoT (Baglin et al., 2006), and Kepler (Borucki et al., 2007) will soon allow additional tests of dynamo models using other solar-type stars (see Metcalfe et al. 2007, Chaplin et al. 2007). High precision time-series photometry from MOST has already revealed latitudinal differential rotation in two solar-type stars (Croll et al. 2006; Walker et al. 2007), and the long-term monitoring from future satellite missions and from ground-based networks such as the Stellar Oscillations Network Group (SONG) are expected to yield the precision necessary for asteroseismic measurements of stellar convection zone depths (Monteiro et al. 2000; Verner et al. 2006). By combining such observations with the stellar magnetic activity cycles documented from long-term monitoring of the Ca II H and K lines, we can extend the calibration of dynamo models from the solar case to a broad range of F, G, and K stars. Adding interferometric measurements of stellar radii to this mix will also be desirable, since this will strengthen constraints on fundamental stellar properties such as mass (Creevey et al. 2007).

Magnetic fields and temporal variability of stars are also important because they affect conditions on any attendant planets. The influence of the Sun on the Earth and its climate is of course the subject of much work, and processes involving the solar wind and UV flux have been critical in determining the evolution of the atmospheres of Mars and Venus. Stellar flares and other eruptive phenomena could have a similarly large effect on the habitability of extrasolar planets, especially those orbiting highly variable M dwarfs, which are the focus of several targeted planet search programs. Finally, magnetic activity is often the dominant noise source against which the radial velocity signal from extrasolar planets must be detected. Better characterizing stellar activity and its radiative signatures may be essential for isolating a numerous sample of planets circling young, magnetically-active stars, and for confirming the many exoplanet candidates expected from Kepler.

⁴<http://atst.nso.edu/>

⁵<http://sdo.gsfc.nasa.gov/>

6 Summary

Magnetic fields and dynamo processes play key roles in astrophysical phenomena that range in scale from the dissipation length in flare kernels up to the size of galaxies. On Earth, a confluence of technical progress and broadening context has both created opportunities and heightened motivation to mount a systematic attack on the problem of stellar magnetic activity. For now, therefore, the most promising environment in which to study these processes is on the intermediate scale, in stars.

If we could achieve a coherent picture of magnetic fields in stars, it would illuminate many seemingly disparate phenomena. Stellar activity cycles, stellar winds, angular momentum loss, and ages, formation of young stars, irradiation and ablation of planetary atmospheres, and high-energy flaring would then be treatable as closely-linked and consistent processes.

Carrying out this line of research will require detailed study of the Sun, using the most capable observing methods, the most innovative phenomenological models, and the highest-resolution numerical simulations. It will also require a comprehensive extension of these methods to a wide variety of other stars. We know that different stars display a great range of differing dynamo-related phenomena; to capture the subtleties of the highly nonlinear magnetic interactions, we will be forced to probe all of their behaviors. Fortunately, the tools to do this are at hand. Spaceborne photometry missions, ground-based robotic telescopes, and massive expansion of computing power are the enabling technologies; with adequate support, international cooperation and imaginative scientific programs will provide the needed organization.

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